Stratospheric variability and its dynamical impact on the troposphere simulated by chemistry-climate models

Daniele Minganti

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Mean state of the atmosphere

\[ \frac{\partial u_g}{\partial z} = -\frac{R}{Hf_0} \frac{\partial T}{\partial y} \]

[Holton, 2004]

Thermal wind relationship


Observed monthly and zonally averaged temperature (K) and zonal wind (m/s) for the month of January

[Holton, 2004]
Wave-driven (B-D) circulation

[Diagram of atmospheric circulation showing regions of gravity waves, planetary (Rossby) waves, and synoptic scale waves.]

Gravity waves

Planetary (Rossby) waves

Synoptic scale waves

Hadley cell branches

Residual mean meridional circulation:

\[
\bar{v}^* \equiv \bar{v} - \rho_0^{-1}(\rho_0 \bar{v}' \bar{\theta}')/\bar{\theta}_z \\
\bar{w}^* \equiv \bar{w} + (a \cos \phi)^{-1}(\cos \phi \bar{v}' \bar{\theta}'/\bar{\theta}_z)_\phi
\]

Eddy heat flux, effect of waves

[Andrews et al., 1987]

[after Plumb, 2002]
Aim of the work

- Study of the *stratospheric variability*, in particular the wintertime Northern Hemisphere (*NH*) polar stratosphere, and its *effect on the tropospheric circulation*.

- A number of *Chemistry-Climate Model (CCM)* simulations is used to evaluate such coupling, together with the "observational" data from *ERA-interim reanalysis*.

- Characterization of *anomalous stratospheric events* and their effects on the tropospheric circulation.

- Implications: evaluation of the *stratosphere as source of predictability* both for climate and weather prediction.
**NH dynamics**

- **Sudden Stratospheric Warming (SSW):** in the winter season the tropospheric waves can interact with the stratosphere, leading to a *warming of the stratosphere* (up to 40° C) and, in the most severe cases, a *reversal* of the *westerly circulation* is observed. This leads to a *weakening* of the *polar vortex*.

\[
0 < \bar{u} < \beta \left[ \left( k^2 + l^2 \right) + f_0^2 / \left( 4N^2 H^2 \right) \right]^{-1} \equiv U_c,
\]

**Condition for vertical propagation of stationary (Rossby) waves into the stratosphere**

\[
f_0 \equiv 2\Omega \sin \phi_0
\]

\[
\beta \equiv 2\Omega a^{-1} \cos \phi_0
\]

\[
N^2 = g \frac{d \ln \theta_0}{dz}
\]

**Brunt-Vaisala frequency**

\[U_c\] is the *Rossby critical velocity*

**Temperature at 10 hPa**
**NH dynamics**

- **Annular Modes**: hemispheric variability (pressure, wind), produced by atmospheric mass redistribution, and present at all levels. **Positive phase**: negative pressure anomalies over the Pole, and positive pressure anomalies over the mid-latitudes.

  **Negative phase** of the NAM is related to weak polar vortex regimes.

  ![Leading structures of the monthly mean 50 hPa height anomaly field for November (SH, left) and Jan-Mar (NH, right).](image)

**NAM**: Northern Annular Mode (AO, NAO)

[Thompson and Wallace, 1999]
Stratospheric variability: strato-tropo coupling

Composites of time-height development of NAM (dimensionless).

Events determined by the dates on which the 10 hPa annular mode values cross -3.0 and +1.5.

These values are highly correlated (0.95) to with $u$ at 10 hPa, 60N.

- **Red**: polar vortex warm and weak.
- **Blue**: polar vortex cold and strong.

Positive values (+1.5) == strong vortex
Negative values (-3.0) == weak vortex

[Baldwin and Dunkerton 2001]
**Stratospheric variability: strato-tropo coupling**

Stratospheric anomalous event January 2014

Record of cold temperatures

[Sigmond et al., 2013]

Chicago on January 7, 2014

https://www.climate.gov/news-features/event-tracker/wobbly-polar-vortex-triggers-extreme-cold-air-outbreak

Enhanced seasonal forecast skill following stratospheric sudden warmings [Sigmond et al., 2013]

M. Sigmond, J. F. Scinocca, V. V. Kharin and T. G. Shepherd

The predictability of the extratropical stratosphere on monthly time-scales and its impact on the skill of tropospheric forecasts

Om P. Tripathi, Mark Baldwin, Andrew Charlton-Perez, Martin Charron, Stephen D. Eckermann, Edwin Gerber, R. Giles Harrison, David R. Jackson, Baek-Min Kim, Yuhji Kuroda, Andrea Lang, Sana Mahmood, Ryo Mizuta, Greg Roff, Michael Sigmond and Seok-Woo Son

Extreme stratospheric events improve wintertime tropospheric predictability.

[Tripathi et al., 2015]
METHODOLOGY

- CCM structure
- SSW events detection
- NAM regimes characterization
Chemistry-Climate Model structure

- **Chemistry**: solving equation governing (among all) stratospheric ozone. Several schemes of inorganic chemistry included.

- **Radiation**: Separation of shortwave (SW) and longwave (LW) spectrum. Increased resolution (SW) for ozone.

- **Dynamics**: temporal evolution of the wind, pressure, etc. Solving equations on discrete spatial and temporal grid. Sub-grid processes are parametrized.
Identification of stratospheric anomalies: SSW

- **Date of occurrence** index (discrete): based on the definition used by [Charlton and Polvani, 2007].

- A SSW occurs when the zonal mean zonal wind at 60°N and 10 hPa becomes easterly, and the temperature gradient between 60°N and 90°N becomes positive during winter (November-March)(NDJFM).

- The central date: first day on which those conditions are met.

- **Final warming** (zonal wind easterly, but not returning westerly for 10 days before 30 April) and **minor warming** (only temperature gradient condition) are not included in this analysis.

- Shortest duration: 4 days. Minimum distance between events: 20 days

Geopotential height on the 10 hPa pressure surface. Shading shows potential vorticity greater than a threshold value (*polar vortex*).

[Charlton and Polvani, 2007]
Identification of stratospheric anomalies: NAM regimes

- **NAM index** (continue): based on the methodology reported by [Baldwin and Thompson, 2009].

- NAM is defined as the leading Empirical Orthogonal Function (EOF) of the NH (20°-90°N) winter zonal mean geopotential height anomalies at 10 hPa.

- The index is the standardized Principal Component (PC) of the leading EOF ($k=1$).

- Events of "strong" (95% prct) and "weak" (5% prct) vortex.

- Minimum duration of the event: three days. Minimum distance between two events: 30 days.
CCMs and reanalysis

**CMAM(1960-2000)**
- Resolution: 3.75x3.75 lat,lon (≈415x415 km)
- Uppermost level: ≈100 km (8.1*10-7 hPa), 71 levels
- Used in operational seasonal forecast simulations from the Canadian Centre for Climate Modelling and Analysis (CCCma).

**NIWA(1960-1999)**
- Resolution: 2.75x3.75 lat,lon (≈272x415 km)
- Uppermost level: ≈84 km (0.1 hPa), 31 levels

**ERA-interim(1979-present)(ERA)**
- Resolution: 1x1 lat,lon (≈110x110 km)
- Uppermost level: ≈54 km (1 hPa), 37 levels
- Dataset created via data assimilation scheme (combining observations and forecast output from a weather model): at all times and spatial grid points.

[Dee et al., 2011]

**Considered models:**
- **CCSRNIES** [Akiyoshi et al. (2009)]
- **CMAM** [Scinocca et al. (2008)]
- **HadGEM3** [Walters et al. (2011)]
- **MRI** [Shibata and Deushi (2008)]
- **NIWA** [Morgenstern et al. (2013)]
- **SOCOL** [Stenke et al. (2012)]
RESULTS
Atmospheric mean state (DJF) and interannual variability

Zonal wind

- **ERA**
  - 30-35 m/s

- **CMAM**
  - Weak jet (20-25 m/s)

- **NIWA**
  - Strong jet (45-50 m/s)

Temperature

- **ERA**
  - 215 K

- **CMAM**
  - 215-220 K

- **NIWA**
  - Cold bias (210 K)

Contours every 5 m/s and 5 K

Gray shading: variability

Heights (hPa):

- North Pole
- Latitude

Dimensions: 794.0x595.0
Intraseasonal SSW distribution

High frequency in mid-winter (Jan, Feb)
Few events in Dec and March

Accordance with reanalysis (correct seasonal cycle), higher number of events

Seasonal cycle not reproduced (few events)

Few events and cold bias
Interannual SSW distribution

High frequency in mid-winter (Jan, Feb)
Few events in Dec and March

Accordance with reanalysis (correct seasonal cycle), higher number of events

Multi-annual SSW distribution (low frequency variability)

Few events and cold bias

Seasonal cycle not reproduced (few events)
Downward propagation: SSW

$[u']$ is the zonal mean zonal wind anomaly (all anomalies calculated w.r.t. daily mean over all years)

Delayed downward propagation of the negative zonal wind anomaly after SSW events.

ERA: clear representation.
CMAM: present but not as strong as ERA.
NIWA: not realistic representation (few events).
**Weak vortex NAM index**

Contour every 5 m/s

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Delayed downward propagation of the negative zonal wind anomaly after NAM weak vortex events.

**ERA**: clear representation.
**CMAM**: quite similar to ERA.
**NIWA**: not realistic representation.
Delayed downward propagation of the negative zonal wind anomaly after NAM weak vortex events

**ERA:** clear representation.

**CMAM:** quite similar to ERA.

**NIWA:** not realistic representation.
Weak vortex 30 days before

Composites of 500 hPa geopotential height anomalies (m)

Tropospheric pattern resembling Atlantic blocking event

SSW preconditioning (most SSW preceded by Atlantic blocking)

[Martius et al., 2009]
Weak vortex 30 days after

Composites of 500 hPa geopotential height anomalies (m)

Atlantic sector of the NAM (NAO)

Contours every 10 m

Anomalies affecting high and low latitudes (negative phase of the NAM represented)

Few significant anomalies (negative phase of the NAM not represented)

Anomalies affecting high and low latitudes. Different pattern from the reanalysis (negative phase of the NAM on the Atlantic sector well represented)
Strong vortex NAM index

Contour every 5 m/s

Delayed downward propagation of the positive zonal wind anomaly after NAM strong vortex events

ERA: clear representation.
CMAM: quite similar to ERA.
NIWA: not realistic representation.
**Strong vortex 30 days before**

Composites of 500 hPa geopotential height anomalies (m)

Tropospheric pattern: dipole at high latitudes and positive anomaly at mid-latitudes

Pattern similar to the reanalysis at high latitudes

Different pattern from the reanalysis and smaller patterns of confidence (larger than weak vortex)
Contours every 10 m

**Strong vortex 30 days after**

Positive significant anomalies. Negative anomalies are smaller. Positive NAM phase is reproduced.

Different pattern from the reanalysis (positive NAM phase not represented).
Conclusions

- A comparison between CCMI models and reanalysis was made looking at the strat-tropo dynamical coupling using SSW and NAM indices.
- Possibility for better predictions of mid-latitude "weather" in weak and strong vortex regimes, requires models with a good representation of this coupling.
- Stratospheric variability (strong/weak polar vortex regimes in particular) is highly related to the mean state: reduced stratospheric variability is correlated with a colder polar stratosphere (e.g. NIWA).
- Weak vortex regimes seem to be preceded by tropospheric pattern resembling blocking event, in ERA but not in CMAM and NIWA.
- Models that do not show correct stratospheric variability, tend to have a uncorrect simulation of the NAM in the troposphere.

Perspectives:
- a) Extend analysis to all 14 models in CCMI dataset.
- b) Create a metrics to compare stratosphere-troposphere coupling between different models.
References

• Thompson and Wallace, JGR, 1999
• Plumb, JMSJap, 2002
• Holton, 2004
• Baldwin and Dunkerton, Science, 2001
• Charlton and Polvani, AMS, 2007
• Baldwin and Thompson, QJRMeteorSoc, 2009
• Dee et al., QJRMeteorSoc, 2011
• Sigmond et al., Nature Geoscience, 2013
• Tripathi et al., QJRMeteorSoc, 2015
• Martius et al., GRL, 2009
• Akiyoshi et al., JGR, 2013
• Scinocca et al., ACP, 2008
• Walters et al., GMD, 2011
• Shibata and Deushi, AnGeo, 2008
• Morgenstern et al., JGR 2013
• Stenke et al., GMDD, 2012
## Backing slides

### Models characteristics

<table>
<thead>
<tr>
<th>Model name</th>
<th>Resolution</th>
<th>Uppermost Level</th>
<th>Chemistry</th>
<th>ODS/GHG Emission</th>
<th>Ocean</th>
<th>QBO</th>
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<tbody>
<tr>
<td>CMAM</td>
<td>T47</td>
<td>0,00081 hPa</td>
<td>Strat-trop</td>
<td>N.A.</td>
<td>Fixed</td>
<td>Internal</td>
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<td>CCSRNIES</td>
<td>T42/L34</td>
<td>0,012 hPa</td>
<td>Strat.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>Nudged</td>
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<tr>
<td>HadGEM3</td>
<td>1,25/1,875 L85</td>
<td>84 km</td>
<td>Strat-trop</td>
<td>N.A.</td>
<td>Coupled</td>
<td>N.A.</td>
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<tr>
<td>MRI</td>
<td>T42</td>
<td>0,01 hPa</td>
<td>Strat-trop</td>
<td>N.A.</td>
<td>Coupled</td>
<td>Internal</td>
</tr>
<tr>
<td>NIWA</td>
<td>2,5/3,75 L60</td>
<td>84 km</td>
<td>Strat-trop</td>
<td>Mixing Ratio</td>
<td>Coupled</td>
<td>Internal</td>
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<tr>
<td>SOCOL</td>
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<td>Strat</td>
<td>N.A.</td>
<td>N.A.</td>
<td>Nudged</td>
</tr>
</tbody>
</table>

Detailed informations about the forcings can be found in:

[Eyring et al., SPARC Newsletter, 2013]
Backimg slides

NIWA

Standardized PC

Leading EOF

NIWA-UKCA first EOF 10 hPa 20-90N zmzg anomalies, explained variance=94.4%
First EOF SH for ERA-interim

first EOF 10 hPa 20-90S zmzg, explained variance=90.9%
Differences indeces in [Baldwin and Thompson, 2009]

**Surface-based NAM**

- 300 hPa
- Difficult reproduction of upper stratosphere annular modes.

**Height-dependent NAM**

- 300 hPa
- Robust at stratosphere and surface, but not at upper troposphere.

**Zonal-mean NAM**

- 300 hPa
- Less dependent on subjective choice, higher correlation between strat-trop varib, requires less data.